

Is chiral symmetry broken and or restored in high-mass light baryons ?

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Based on a thorough comparison of the nucleon and Δ excitation spectrum with models we show that parity doublets observed in the mass spectra do not entail the consequence that highly excited N or Δ resonances are insensitive to chiral symmetry breaking. Instead, the mechanism of mass generation in excited states is suggested to be the same as for the baryon ground states: the mass is assigned to fluctuating gluon fields and their strong attraction. In excited baryons, the field energy has to be integrated over a larger volume, and the total mass increases. Thus, also the additional mass of resonances, the excitation energy, is generated by spontaneous breaking of chiral symmetry.

PACS numbers: 11.30.Rd, 12.39.-x, 14.20, 14.40.Be

SU(3) symmetry and the conjecture that mesons and baryons are composed of constituent quarks [1, 2] paved the path to an understanding of the particle zoo. A constituent light-quark mass of about 350 MeV was required to reproduce the masses of ground-state baryons; the N - Δ (1232) mass splitting and the pattern of negative- and positive-parity excited baryons was interpreted as an effect of a QCD hyperfine interaction between these constituent quarks [3, 4]. However, low-energy approximations of QCD [5] lead to the Gell-Mann-Oakes-Renner relation [6] which assigns a mass of a few MeV to light (current) quarks. The mass gap between current and constituent quarks is interpreted by spontaneous breaking of the chiral symmetry expected for nearly massless quarks [7, 8]. An important consequence is the large mass gap between chiral partners: the masses of the nucleon, with spin-parity $J^P = 1/2^+$, and its chiral partner $N_{1/2^-}$ (1535), with spin-parity $J^P = 1/2^-$ and mass $M = 1535$ MeV, differ by about 600 MeV.

In the higher mass region, parity doublets are observed and often, nucleon and Δ resonances of given spin and parity form a quartet of mass-degenerate states. Most convincing examples are the light-quark baryons in the third and forth resonance region (see Table I). In both regions, two mass-degenerate spin-isospin quartets with $J^P = 1/2^\pm$ and $J^P = 3/2^\pm$, respectively, can be identified (in the first and second column). In the third region, a $J = 5/2^\pm$ parity doublet of nucleon resonances, in the forth region, a $J^P = 5/2^\pm$ parity doublet of Δ resonances can be recognized. A parity partner of $N_{5/2^+}$ (2000) is missing. $N_{1/2^+}$ (1440) and $N_{1/2^-}$ (1535) in the 2nd resonance region are not really mass-degenerate, $\Delta_{3/2^+}$ (1232) and $N_{3/2^-}$ (1520) have no close-by parity partner; the 1st and 2nd resonance regions do not yet belong to the highly excited states.

The observation of parity doublets has led to the conjecture that chiral symmetry might be effectively restored in highly excited baryons [9]. The mass generation mechanism in excited hadrons is, according to Glozman [10], very different compared to the mechanism in the lower-mass states. In the latter states, the mass is supposed

to be driven by chiral symmetry breaking in the vacuum, by the quark condensate. For highly excited states, the quark condensate is believed to be almost irrelevant and the mass of resonances within a parity doublet could have a chirally symmetric origin.

The conjecture of chiral symmetry restoration of highly excited hadrons has been worked out in a number of papers, we quote a few recent reviews [11]. Particularly exciting would be the possibility to track the transition from constituent quarks to current quarks by precise measurements of the masses of excited hadron resonances [12]. A weak attraction between parity partners in the 2 GeV mass region – as suggested by phenomenology – can possibly be interpreted as onset of a regime in which chiral symmetry is restored [13]. This interpretation depends, of course, crucially on the assumption that chiral symmetry breaking plays no role in the high-mass part of the hadron excitation spectrum.

If chiral symmetry is at work in highly excited baryons, a few additional states must exist which are indicated

Table I: Light-quark nucleon (N) and Δ resonances in the 1st, 2nd, 3rd, and 4th resonance region (rr). The spin-parities J^P of resonances are given as subscripts.

$J^P = 1/2^\pm$	$3/2^\pm$	$5/2^\pm$	$7/2^\pm$	rr
	$\Delta_{3/2^+}$ (1232)			1 st
$N_{1/2^-}$ (1535)	$N_{3/2^-}$ (1520)			2 nd
$N_{1/2^+}$ (1440)				
$N_{1/2^-}$ (1650)	$N_{3/2^-}$ (1700)	$N_{5/2^-}$ (1675)		3 rd
$N_{1/2^+}$ (1710)	$N_{3/2^+}$ (1720)	$N_{5/2^+}$ (1680)		
$\Delta_{1/2^-}$ (1620)	$\Delta_{3/2^-}$ (1700)			
$\Delta_{1/2^+}$ (1750)	$\Delta_{3/2^+}$ (1600)			
$N_{1/2^-}$ (1885) ¹	$N_{3/2^-}$ (1875) ¹	?	?	4 th
$N_{1/2^+}$ (1880) ¹	$N_{3/2^+}$ (1900)	$N_{5/2^+}$ (2000)	$N_{7/2^+}$ (1990)	
$\Delta_{1/2^-}$ (1900)	$\Delta_{3/2^-}$ (1940)	$\Delta_{5/2^-}$ (1930)	?	
$\Delta_{1/2^+}$ (1910)	$\Delta_{3/2^+}$ (1920)	$\Delta_{5/2^+}$ (1905)	$\Delta_{7/2^+}$ (1950)	

¹ States not reported in [15] but observed in the Bonn-Gatchina multichannel partial wave analysis [17].

by question marks in Table I. Candidates for these additional states are $N_{5/2-}$ (2200), $N_{7/2-}$ (2190), and $\Delta_{7/2-}$ (2200), respectively. The three states are separated from their parity partners by about 220 MeV or $\delta M^2 = 0.92 \text{ GeV}^2$ which is suspiciously close to the string tension characterizing the slope of baryon Regge trajectories (1.06 GeV^2). Hence the question must be answered if the absence (or “wrong” mass) of some states – expected in scenarios with chiral symmetry restoration – is due to lacking experimental information, or if we can understand the reason why some resonances have parity partners and others not.

In this letter we discuss a dynamical origin of the occurrence of parity doublets in the mass spectrum of mesons and baryons and show that parity doublets in high-mass hadrons do not need to signal chiral symmetry. On the contrary, parity doublets could be the consequence of chiral symmetry breaking in an extended volume. The conclusions are derived from a thorough comparison of the experimental mass spectrum of nucleon and $\Delta(1232)$ resonances [36] with the conjecture that chiral symmetry is restored [10], with quark model predictions [18, 19], with the Skyrme model [20], and with predictions of an analytically solvable “gravitational” theory simulating QCD [21–24] which is defined in a five-dimensional Anti-de Sitter (AdS) space embedded in six dimensions. Here, a special variant [25] of AdS/QCD is used.

Quark models are the traditional approach to hadron spectroscopy. The pattern of low-mass states is, perhaps, reasonably well described but the models fail in important details. First, the number of predicted states below, e.g., 2.2 GeV is excessively large, much larger than the number of experimentally known states. This is called the problem of *missing resonances*. Second, the predicted mass pattern is not really adequate. For the Δ excitations, quark models predict a shell structure roughly compatible with the pattern of a harmonic oscillator: a positive-parity ground state, two negative-parity states, followed by a group of positive-parity states, then negative parity, positive parity, \dots . Data do not exhibit the even-odd staggering of masses predicted by quark models. Instead, Δ resonances with even and odd parities cluster at approximately equidistant mass-square values. A χ^2 test of quark models [18, 19] versus experiment thus gives modest agreement only, in spite of a significant number of free parameters. A Skyrme model [20] uses fewer parameters and the agreement with data is worse (see Table II. A detailed comparison can be found in [26]).

In meson spectroscopy, a large number of resonances comes as well in nearly mass degenerate parity doublets, however with important exemptions: Mesons like $f_2(1270)$ and $a_2(1320)$ with $J^{\text{PC}} = 2^{++}$, $\omega_3(1670)$ and $\rho_3(1690)$ with $J^{\text{PC}} = 3^{--}$, $f_4(2050)$ and $a_4(2040)$ with $J^{\text{PC}} = 4^{++}$, none of these states falling onto the lead-

Table II: Comparison of models with data. The number of parameters is given and a “quality” factor. For $Q = 2.5\%$ the rms model deviation from experiment is 50 MeV at 2 GeV corresponding to $\sim 20\%$ of the natural widths. In the high-mass region, a large number of states is predicted by quark models. The smallest mass difference is chosen for the comparison.

Ref.	N_p	Q
[18]	7	$(\delta M/M) = 5.6\%$
[19]	5	$(\delta M/M) = 5.1\%$
[20]	2	$(\delta M/M) = 9.1\%$
[25]	2	$(\delta M/M) = 2.5\%$

ing Regge trajectory has a mass-degenerate spin-parity partner. These are mesons in which the orbital angular momentum L and the total quark spin S are aligned to give the maximal J and which have the lowest mass in that partial wave. Their chiral partners have considerably higher masses: $\eta_2(1645)$ and $\pi_2(1670)$ ($J^{\text{PC}} = 2^{-+}$), $h_3(2045)$ and $b_3(2035)$ ($J^{\text{PC}} = 3^{+-}$), $\eta_4(2320)$ and $\pi_4(2250)$ ($J^{\text{PC}} = 4^{-+}$), respectively [27]. A graphical illustration is given in Fig. 1 of [28] and Fig. 57 of [29].

The meson spectrum is compatible with a simple formula derived in AdS/QCD [23]

$$M^2 = a \cdot (L + N + 1/2) \text{ for mesons} \quad (1)$$

with $a = 1.14 [\text{GeV}^2]$ as Regge slope parameter. The total angular momentum J (the spin of the resonance) does not appear in Eq. (1): the orientation of the total quark spin S along the orbital angular momentum L and the spin-spin interaction – leading to spin singlet- and spin-triplet mesons – have no significant impact on the meson mass, at least not for mesons with $J \neq 0$. Scalar and pseudoscalar mesons are governed by additional forces (by four-quark and meson-meson interactions and, respectively, by their coupling to gluons leading to the $U_A(1)$ anomaly); their masses are not well reproduced by eq. (1). But otherwise, the formula is very successful; in particular it reproduces the correct pattern where parity partners should be observed and where not.

In [30] it is argued that formation of the spin-parity partners of mesons on the leading Regge trajectory could be suppressed by angular momentum barrier factors. A reanalysis of the reaction $\bar{p}p \rightarrow \pi\eta\eta$ in flight [31] was performed and a weak indication claimed [30] for the possible existence of the missing 4^{-+} state $\eta_4(1950)$ at about 1.95 GeV. However, the weakness of the signal is certainly not enforcing any interpretation. Nevertheless, the suppression in $\bar{p}p$ formation of spin-parity partners of mesons on the leading Regge trajectory is certainly an argument which reduces the weight of their non-observation. Hence we go back to baryons.

The conjecture that chiral symmetry is restored gives an interpretation of the mass degeneracy (within a res-

onance region) along vertical lines in Table I; the mass degeneracy along the horizontal lines is still accidental. Here, AdS/QCD is much more powerful. In the variant [25] it predicts

$$M^2 = a \cdot (L + N + 3/2) - b \alpha_D \quad (2)$$

a formula which has been suggested before on an empirical basis [32]. The baryon Regge trajectory requires a slightly softer slope, $a = 1.06 [\text{GeV}^2]$. L is the total intrinsic orbital angular momentum and N the radial quantum number. Quark models of baryons have two oscillators (like any bound three-body problem), and hence four quantum numbers l_1, l_2, n_1, n_2 . Eq. (2) contains L and N only. AdS/QCD predicts therefore a much smaller number of states. α_D is the fraction of *good diquarks* in the baryon, of diquarks with zero spin and isospin. The good-diquark fraction can be calculated from standard quark-model wave functions. It is $1/2$ in the nucleon, $1/4$ in the $N_{1/2-}(1535)/N_{3/2-}(1520)$ spin doublet, and it is assumed to be $1/2$ ($1/4$) for all spin- $1/2$ nucleon resonances in $SU(6)$ 56-plets (70-plets). In spin- $3/2$ nucleon and in Δ excitations, there are no good diquarks. The coefficient $b = 1.46 [\text{GeV}^2]$ gives the best fit. Without this term, the agreement between AdS/QCD and data is considerably worse for negative-parity spin- $1/2$ nucleons and for all spin- $3/2$ nucleons even if different slopes for negative parity baryons are admitted.

The appearance of the orbital angular momentum L in Eqs. (1) and (2) is intriguing. A discussion has developed if the use of non-relativistic concepts is legitimate for the dynamics of quarks in highly excited states [33]. Even a constituent quark mass of 350 MeV is small compared to the mass of a highly excited hadron, and it can be argued that relativistic effects must be huge. On the other hand, Teramond and Brodsky [34] have shown that bound states in QCD with arbitrary spin and intrinsic angular momentum can be mapped onto string modes in AdS/QCD with defined angular momentum, and that the classification of states with AdS/QCD quantum numbers is hence legitimate. For the moment we put aside doubts concerning the applicability of a non-relativistic notion in hadron spectroscopy and show that it is at least a useful concept.

In Table I, the fifth line exhibits a spin triplet of states. It is natural to assign an intrinsic orbital angular momentum $L = 1$ and total quark spin $S = 3/2$ which couple to a total angular momentum $J = 1/2, 3/2, 5/2$. The three masses are similar, the spin-orbit interaction is obviously small, and also mixing with other states having the same quantum numbers does not have a significant impact on the masses. (The three states in the sixth line do not form a spin triplet but a spin singlet with $L = 0$ and a spin doublet with $L = 2$.) Likewise, there are two spin quartets of nucleon and Δ excitations with $L = 2$, listed in line 10 and 12 of Table I. The spin doublet $\Delta_{1/2-}(1620)$ and $\Delta_{3/2-}(1700)$ (line 7) has $L = 1$ and

intrinsic spin $S = 1/2$. For $L = 1, S = 3/2$, symmetry arguments enforce $N = 1$, and these states are found in the second but last line of Table I. Their isotopic companions, $N_{1/2-}(1885)$ and $N_{3/2-}(1875)$, can be interpreted as radial excitations of $N_{1/2-}(1535)$ and $N_{3/2-}(1520)$, respectively. The resonances $\Delta_{1/2+}(1600)/N_{1/2+}(1710)$ – and $\Delta_{3/2+}(1750)$ if it exists [17] – can be interpreted as first ($N = 1$)/second ($N = 2$) radial excitations of the respective ground states.

AdS/QCD reproduces the masses of all 44 N and Δ resonances remarkably well using just two parameters, considerably better than other models (see Table II). One parameter in Eq. (2) is related to confinement, the second one accounts for hyperfine effects. It reduces the size of the nucleon by a fraction which depends on α_D . The precision of the mass calculation is by far better than quark model predictions even though the latter have a significantly larger number of parameters. Obviously, AdS/QCD catches the correct variable which governs the excitation spectrum. This is surprising since L and S are not defined in a relativistic situation but only J .

The decisive variable is size. In AdS/QCD, the size of a hadron is limited, either by a so-called *hard wall* beyond which the wave function has to vanish or by a repelling dilaton field which increases quadratically with the extension of the wave function and which is called *soft wall*. In most AdS/QCD approaches to hadron spectroscopy, a soft wall limits the extent of the wave function. In [25], the second term in Eq. (2) is constructed to reduce the size of the system as a function of the good diquark content. A nucleon is thus smaller than the $\Delta(1232)$.

Why is size important for the mass of a resonance? We first discuss the nucleon mass. In massless QCD, there is no scale in the QCD Lagrangian and hence one should expect the nucleon mass to vanish. But this is obviously wrong. Chiral symmetry is spontaneously broken, and the nucleon mass receives not only contributions from quarks; the fluctuating color-electric and color-magnetic fields \mathbf{E} and \mathbf{B} carry most of the nucleon mass [35]:

$$M_N = \langle N | -\frac{9\alpha_s}{4\pi} (\mathbf{B}^2 - \mathbf{E}^2) + \sum_{\text{flavors}} m_i \bar{\psi}_i \psi_i | N \rangle . \quad (3)$$

The fields need to be integrated over the over the hadron volume. AdS/QCD predicts that the size of a hadron plays the decisive role for its mass. With increasing size, chiral symmetry is spontaneously broken in an extended volume. If the field strengths in Eq. (3) are approximately uniformly spread over the volume, the stored field energy increases with volume and hence the (squared) mass increases. Loosely speaking, the constituent quark mass increases to about $1/3$ of the mass of the resonance. The dynamical degrees of freedom in hadron spectroscopy are thus not constituent quarks having a defined rest mass, a large kinetic energy, and some residual interaction; instead, constituent quark masses are seen to

be ill-defined. In excited hadrons they adopt much larger values, typically $1/3$ of the hadron mass. This justifies, a posteriori, the use of orbital angular momentum L and quark spin S in hadron spectroscopy, quantities which the data demand and which are key quantities in AdS/QCD even though they are not defined in relativistic situations.

Finally we ask if angular momentum barriers may be responsible for the non-observation of the chiral partners of, e.g., $N_{7/2^+}$ (1990) and $\Delta_{7/2^+}$ (1950). In πN elastic scattering, this is indeed the case. In scattering, an angular momentum $L = 3$ is required to form a $7/2^+$ resonance; for $7/2^-$, $L = 4$ is needed. Hence there is still a way to escape the conclusions offered here and to rescue the conjecture of chiral symmetry restoration in highly excited hadrons. This hideout can be closed in photoproduction experiments: a $7/2^+$ resonance requires a E_4^+ or M_4^+ amplitude, a $7/2^-$ resonance a E_3^- or M_3^- amplitude. There is no kinematical factor which would suppress production of $7/2^-$ resonances compared to $7/2^+$ resonances. Photoproduction experiments can thus be of decisive importance to clarify the dynamics of highly excited hadrons.

Summarizing, we have shown that size is the quantity which governs the mass of light-quark baryons. Chiral symmetry breaking, responsible for the proton mass, seems to generate the mass of excited states as well. Likely, there is no chiral symmetry restoration in highly excited baryons. We propose that constituent quarks, if introduced, should not be considered to have a defined rest mass. Instead, their rest mass increases with increasing baryon mass, and the mass of the three constituent quarks accounts for the essential part of the resonance mass. This conjecture provides a natural explanation of the long-standing miracle that the naive non-relativistic quark model is surprisingly successful. We have argued that the search for missing states expected in parity-doublets scenarios should be performed in production and not in formation experiments. Photoproduction of nucleon and Δ resonances with $J^P = 5/2^\pm$ and $7/2^\pm$, expected at masses in the 1.9 to 2.3 GeV mass range, can be decisive to clarify if chiral symmetry is broken or restored in high-mass baryon resonances.

I would like to thank S. J. Brodsky, H. Forkel, U. G. Meißner, V. Metag, G. F. de Teramond, and W. Weise for elucidating discussions and S. J. Brodsky, H. Forkel, and U. G. Meißner for a critical reading of the manuscript. Financial support from the Deutsche Forschungsgemeinschaft (DFG) within SFB/TR16 is kindly acknowledged.

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